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**Marzano et al.**

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(54) **SELECTIVELY INCREMENTALLY ACTUATED LINEAR EDDY CURRENT BRAKING SYSTEM**

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(63) Continuation of application No. 11/058,880, filed on Feb. 16, 2005, now Pat. No. 8,727,078.

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(51) **Int. Cl.**

***B60L 7/00*** (2006.01)
***B60L 7/28*** (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC . ***B60L 7/28*** (2013.01); ***B61H 7/083*** (2013.01); *F16D 63/002* (2013.01); *F16D 2121/24* (2013.01); *F16D 2129/065* (2013.01)

(58) **Field of Classification Search**

CPC ..... F16D 63/00; F16D 63/002; F16D 63/008; F16D 65/00; F16D 65/14; F16D 66/00; F16D 2066/001; F16D 71/00; F16D 2121/18; F16D 2121/24; F16D 2129/06; F16D 2129/065; F16D 2500/00; B60L 7/28; B61H 7/083

USPC ........ 188/71.1, 72.1, 73.1, 73.31, 267, 267.2, 188/156–159, 164, 165; 310/12, 15, 17, 19, 310/22

See application file for complete search history.

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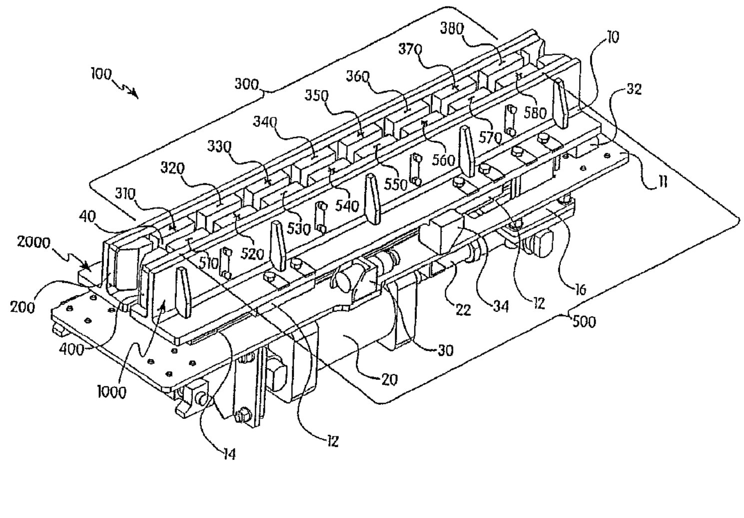
(57) **ABSTRACT**

The invention is an incrementally actuated eddy current braking system. The system comprises first and second primary members, which further comprise arrays of permanent magnets arranged in alternating polarity. The respective magnets of the arrays face one another. A means for incremental displacement is drivingly connected to at least one of the primary members enabling the movement of said members relative to one another.

**20 Claims, 13 Drawing Sheets**



(51) **Int. Cl.**

| | |
|---|---|
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| *F16D 55/00* | (2006.01) |
| *F16D 121/24* | (2012.01) |
| *F16D 129/06* | (2012.01) |
| *F16D 63/00* | (2006.01) |

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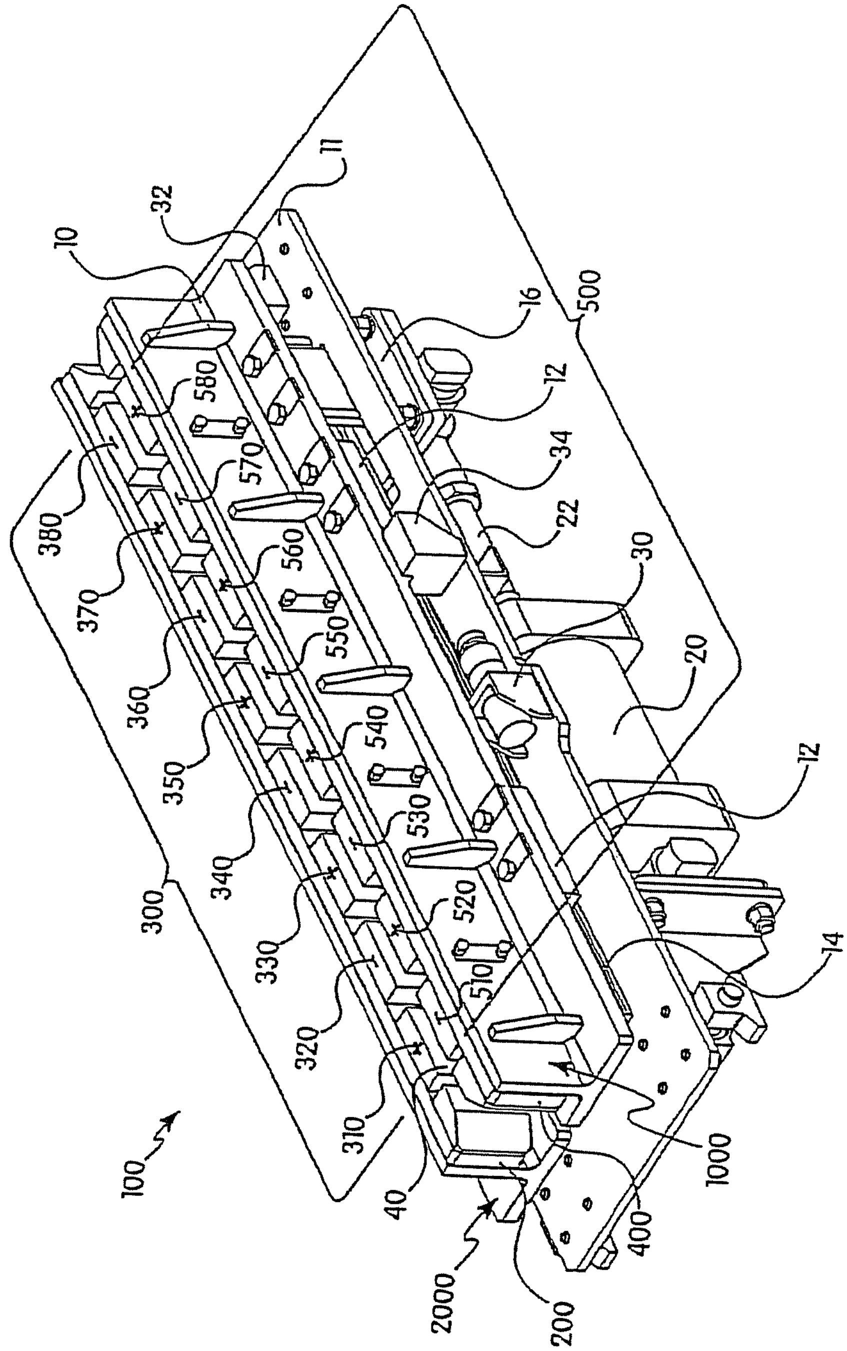

10
32
11
16
500
12
580
570
34
22
380
560
30
370
550
20
360
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12
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520
340
14
300
330
510
320
310
1000
100
40
400
2000
200


FIG. 1

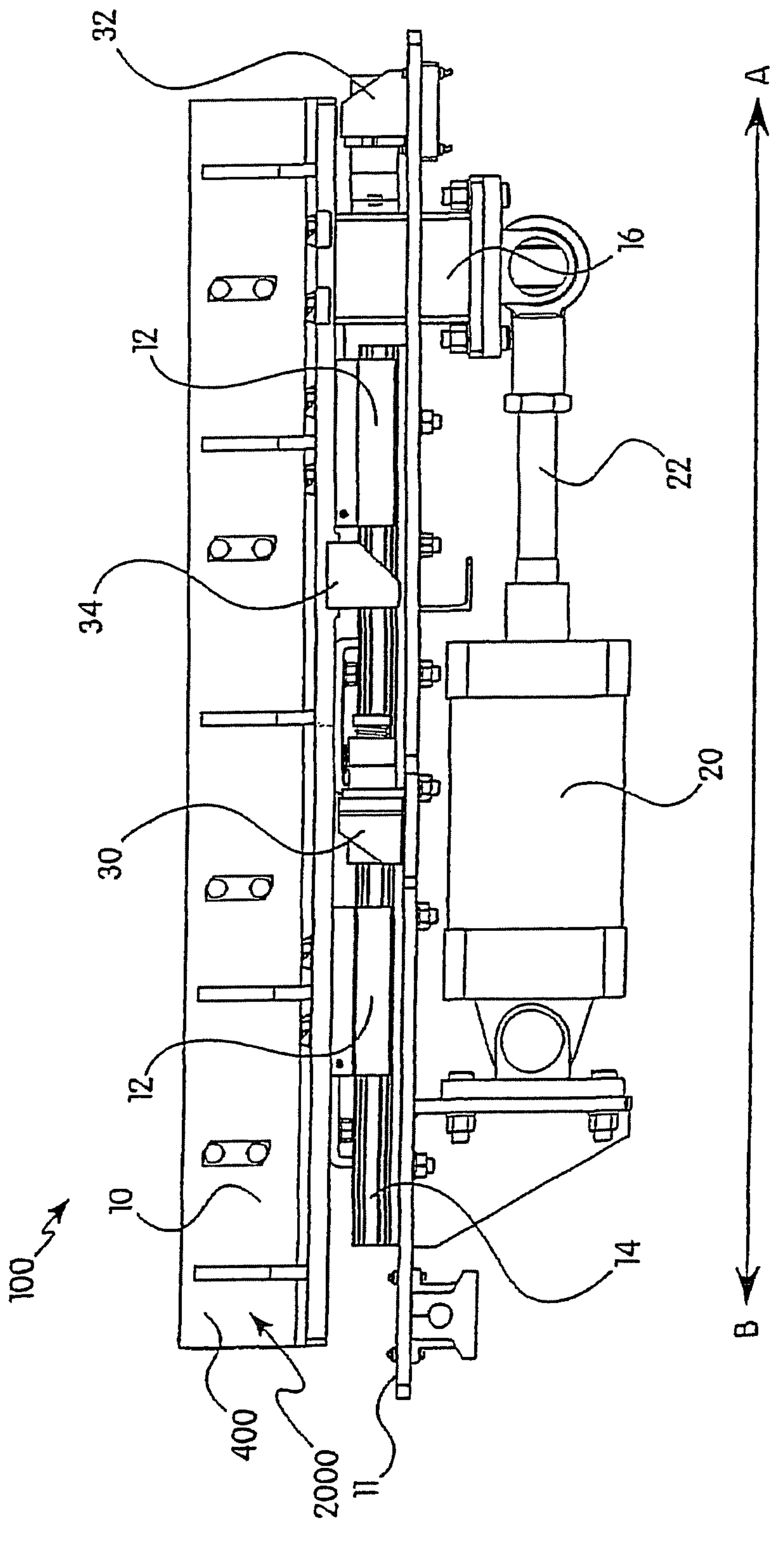


FIG. 2

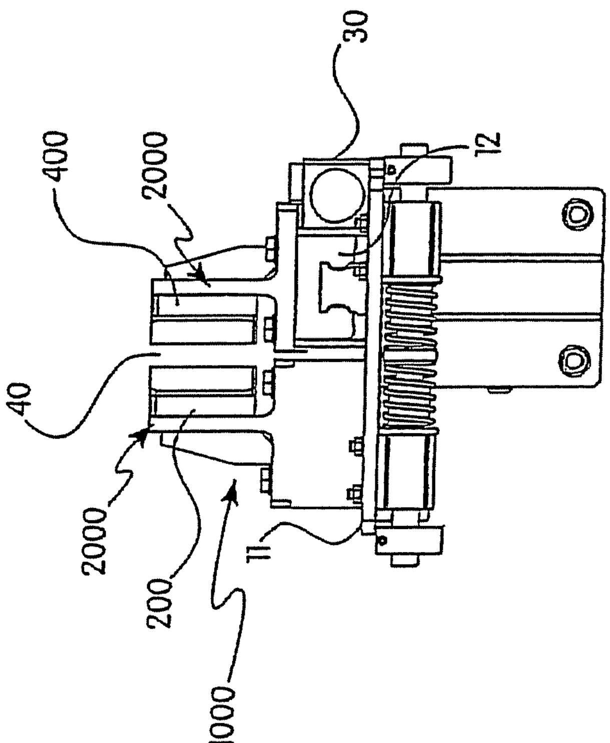


FIG. 3

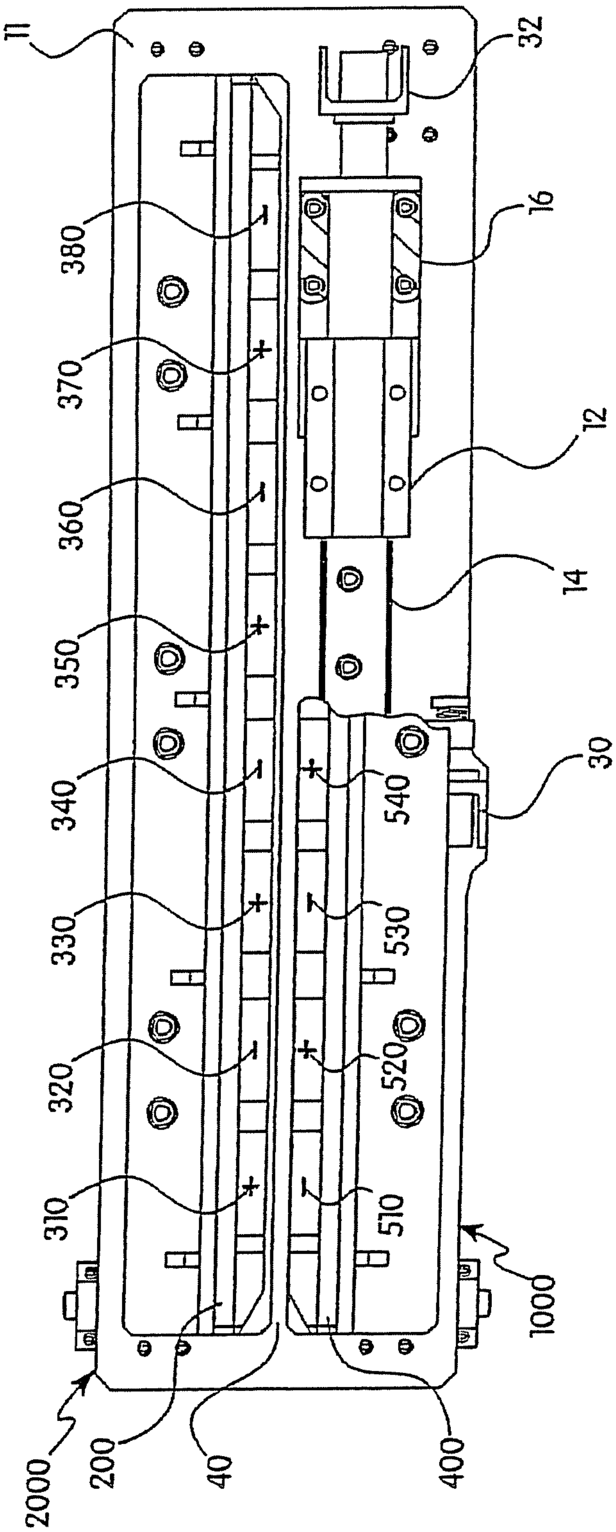
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FIG. 4

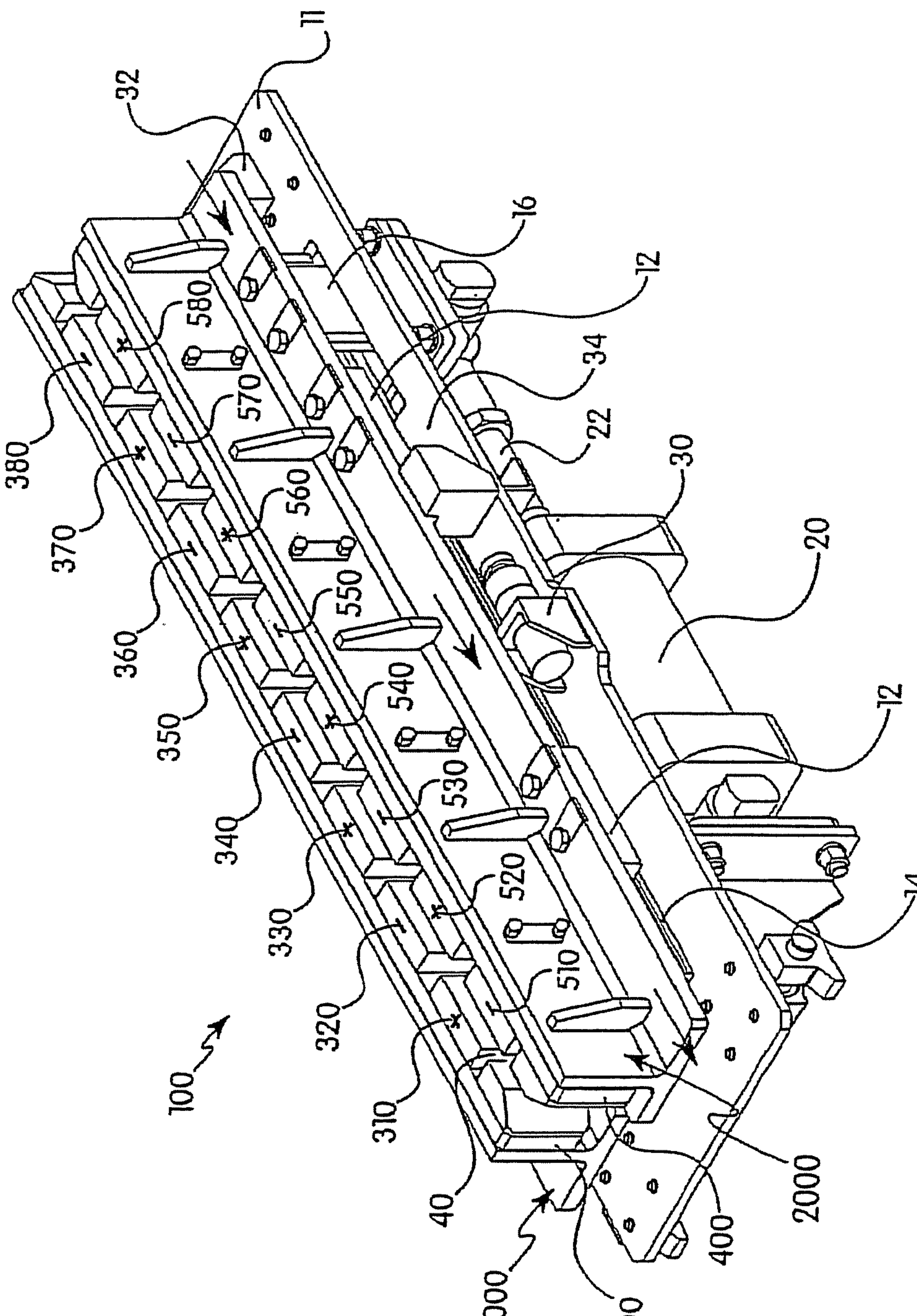

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FIG. 5A

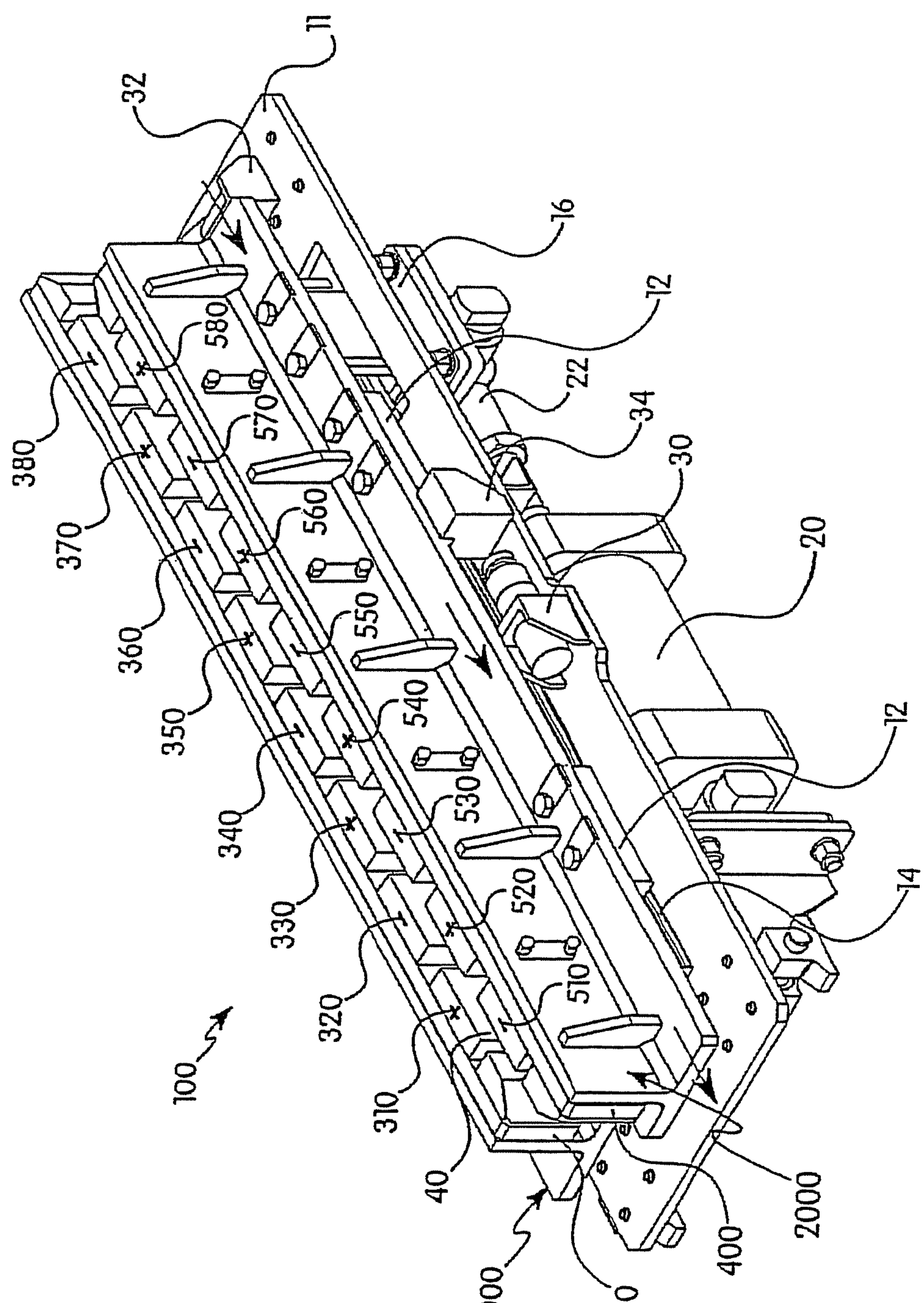
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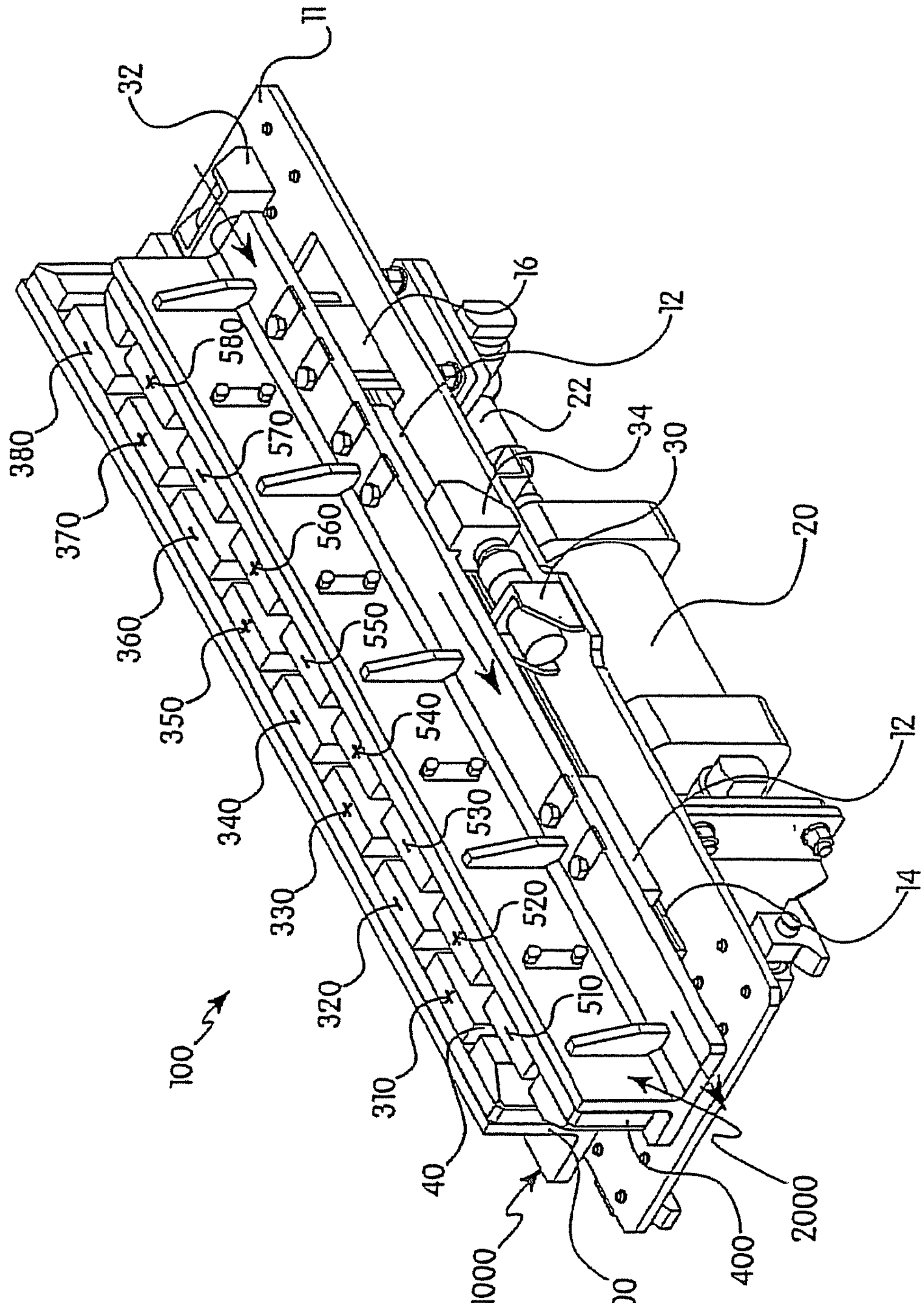
FIG. 5B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540
530
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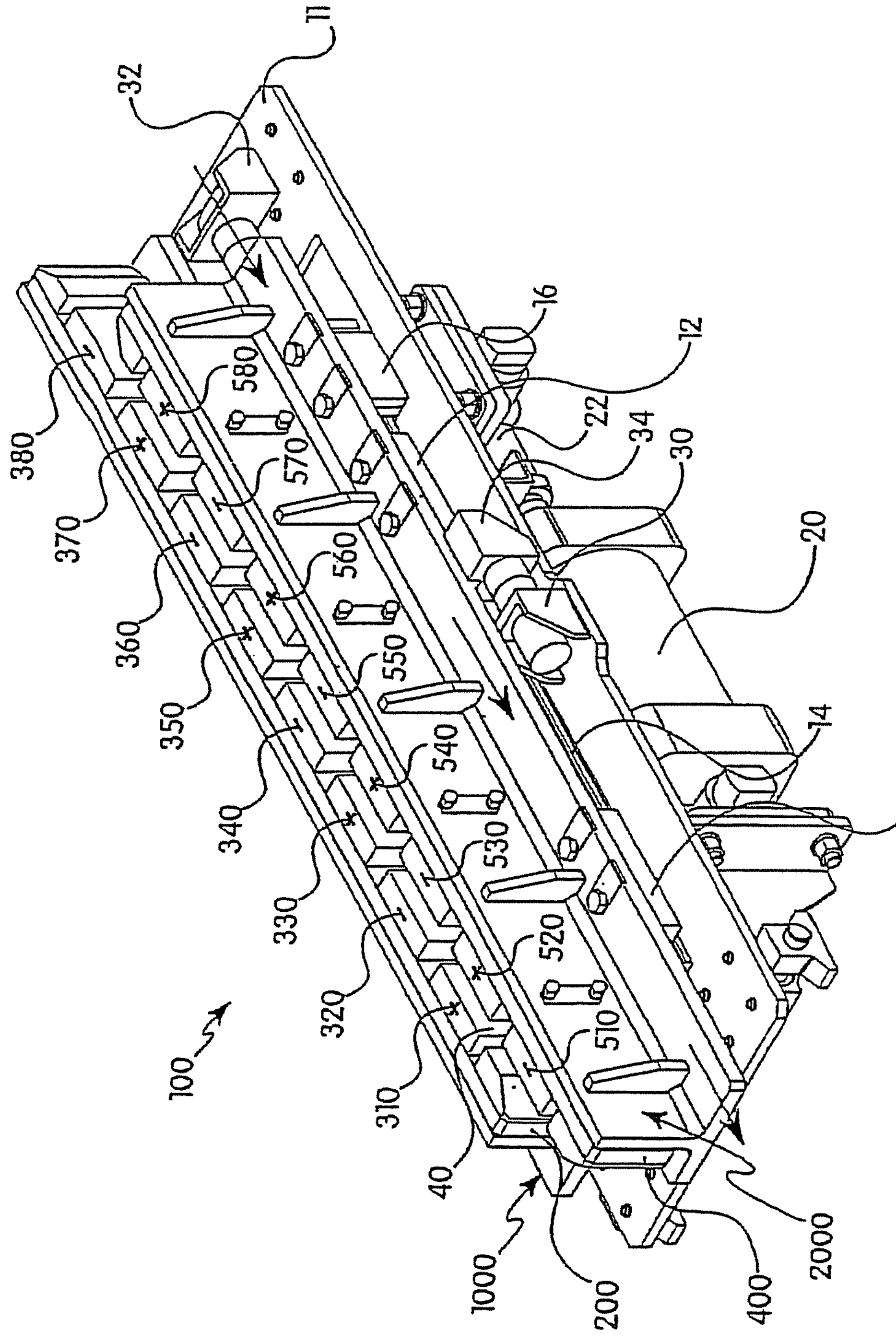
510
100
40
1000
200
400
2000

FIG. 5C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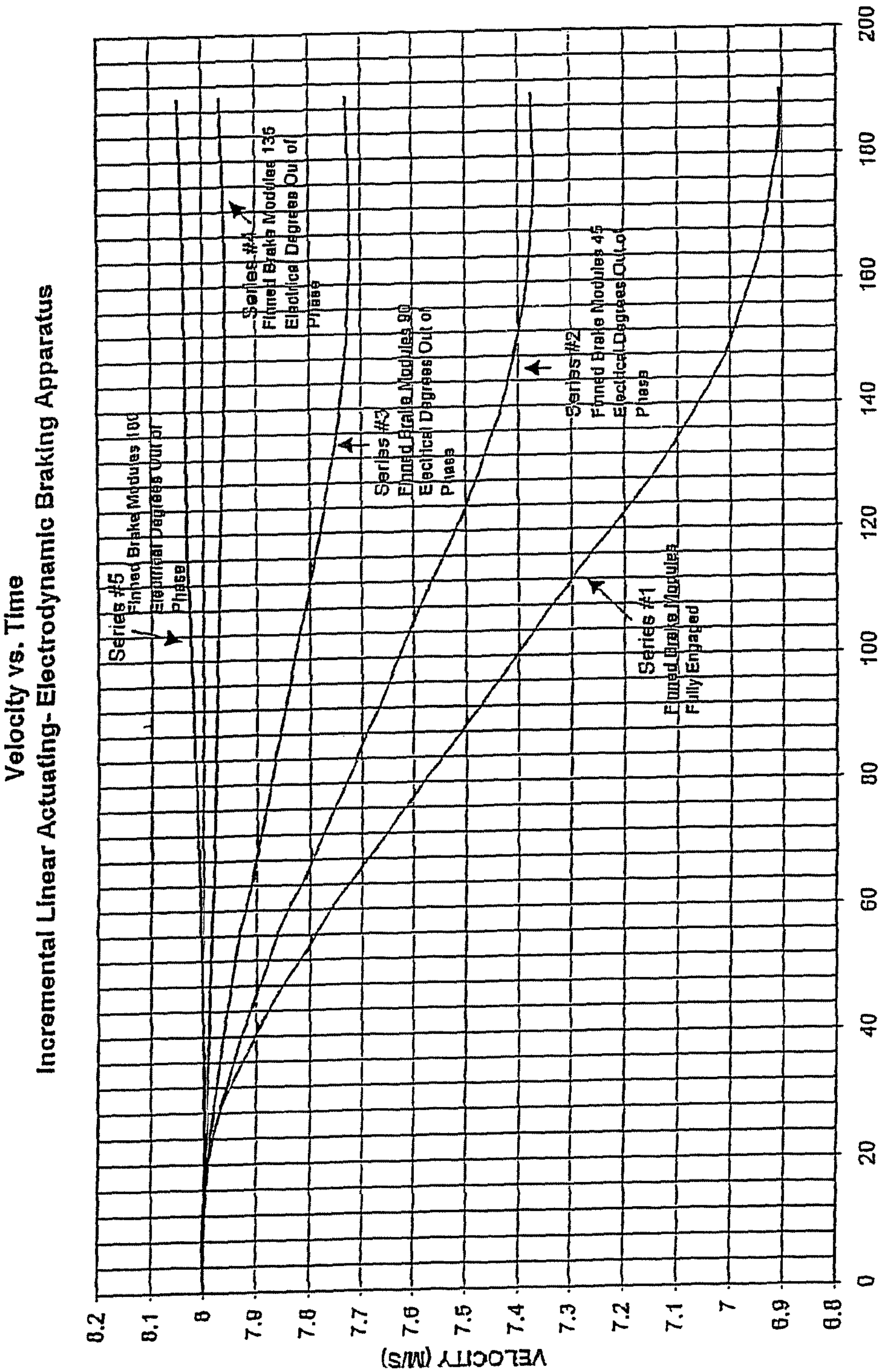
530
320
520
310
510
100
40
1000
200
400
2000

FIG. 5D



Velocity vs. Time
Incremental Linear Actuating- Electrodynamic Braking Apparatus
VELOCITY (M/S)
TIME (ms)
8.2
8.1
8
7.9
7.8
7.7
7.6
7.5
7.4
7.3
7.2
7.1
7
6.9
6.8
0
20
40
60
80
100
120
140
160
180
200
Series #5 Finned Brake Modules 180 Electrical Degrees Out of Phase
Series #4 Finned Brake Modules 135 Electrical Degrees Out of Phase
Series #3 Finned Brake Modules 90 Electrical Degrees Out of Phase
Series #2 Finned Brake Modules 45 Electrical Degrees Out of Phase
Series #1 Finned Brake Modules Fully Engaged


Figure 6

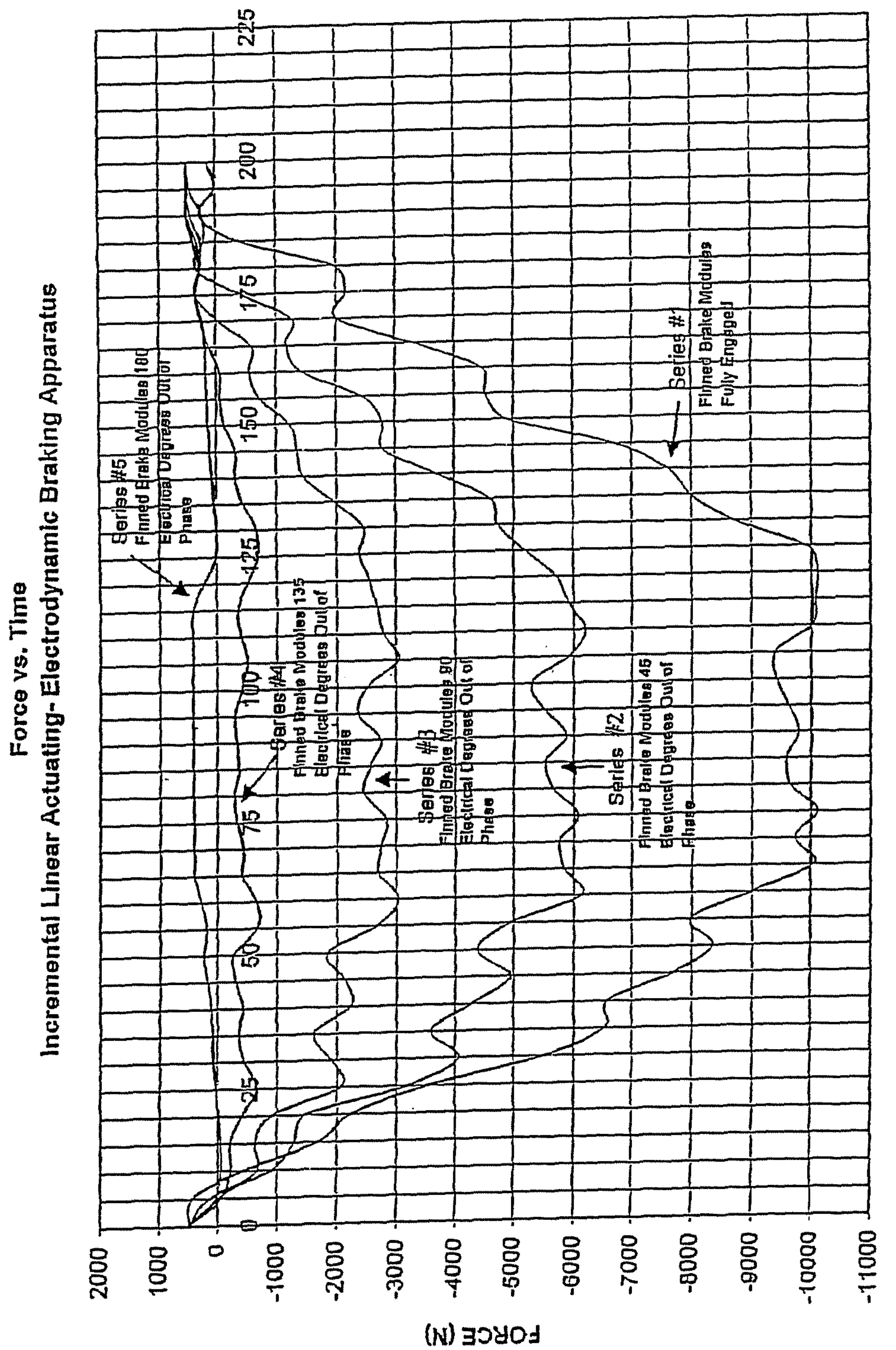
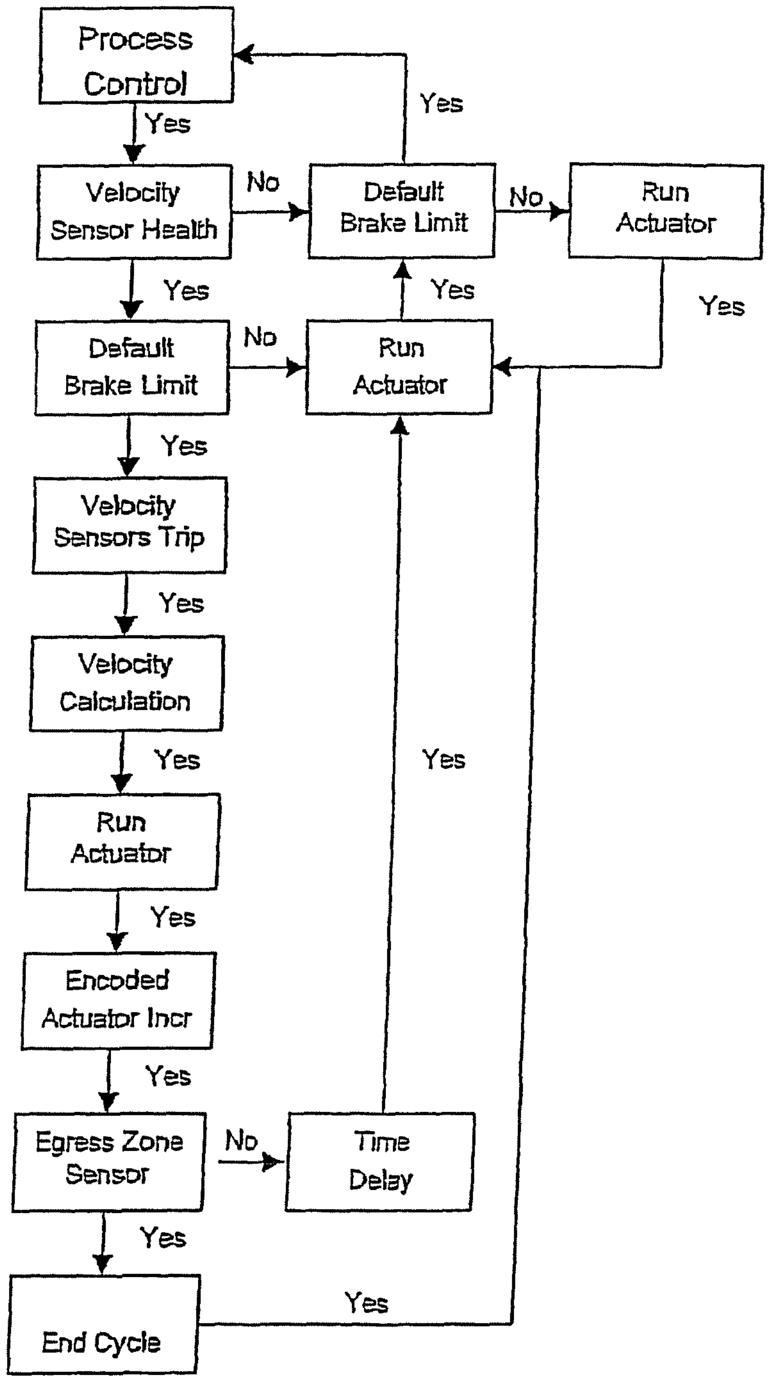

Force vs. Time
Incremental Linear Actuating- Electrodynamic Braking Apparatus
FORCE (N)
TIME (ms)
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
-7000
-8000
-9000
-10000
-11000
0
25
50
75
100
125
150
175
200
225
Series #5
Finned Brake Modules 180
Electrical Degrees Out of
Phase
Series #4
Finned Brake Modules 135
Electrical Degrees Out of
Phase
Series #3
Finned Brake Modules 90
Electrical Degrees Out of
Phase
Series #2
Finned Brake Modules 45
Electrical Degrees Out of
Phase
Series #1
Finned Brake Modules
Fully Engaged

Figure 7



Process Control
Yes
Velocity Sensor Health
No
Default Brake Limit
No
Run Actuator
Yes
Yes
Yes
Default Brake Limit
No
Run Actuator
Yes
Yes
Velocity Sensors Trip
Yes
Velocity Calculation
Yes
Run Actuator
Yes
Encoded Actuator Incr
Yes
Egress Zone Sensor
No
Time Delay
Yes
Yes
End Cycle
Yes


FIG. 8

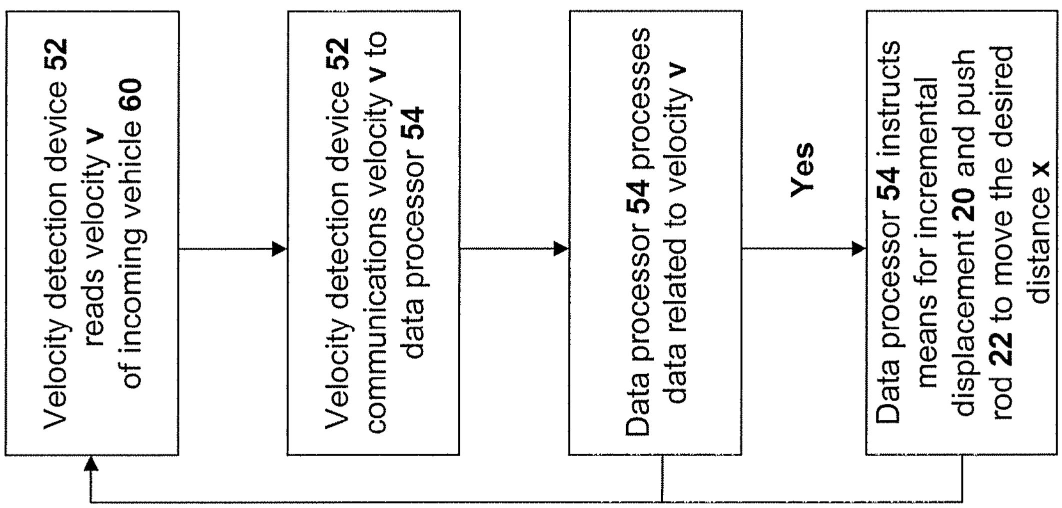
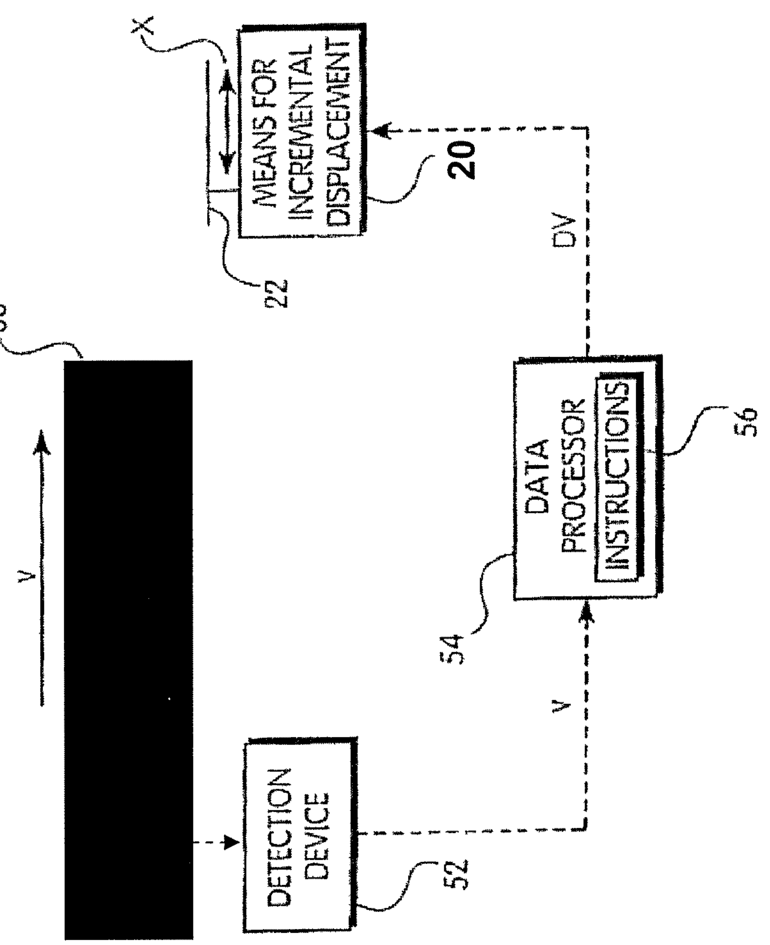

Velocity detection device 52 reads velocity v of incoming vehicle 60
Velocity detection device 52 communications velocity v to data processor 54
Data processor 54 processes data related to velocity v
Yes
Data processor 54 instructs means for incremental displacement 20 and push rod 22 to move the desired distance x

Fig. 9



X
MEANS FOR INCREMENTAL DISPLACEMENT
20
22
DV
60
v
DATA PROCESSOR
INSTRUCTIONS
56
54
v
DETECTION DEVICE
52


FIG. 10

# SELECTIVELY INCREMENTALLY ACTUATED LINEAR EDDY CURRENT BRAKING SYSTEM

## CLAIM OF PRIORITY

This application claims priority of U.S. patent application Ser. No. 11/058,880 filed on Feb. 16, 2005, now U.S. Pat. No. 8,727,078, which claims priority of U.S. Provisional Application No. 60/575,431 filed on May 28, 2004.

## FIELD OF THE INVENTION

This invention relates to a linear synchronous magnetic motor utilized primarily for braking. In particular, this invention relates to a linear synchronous magnetic motor utilized for braking that can be incrementally actuated to allow for the application of the variable braking force.

## BACKGROUND OF THE INVENTION

It is known in the art to provide a linear synchronous magnetic motor as an electrodynamic brake. Such electrodynamic brakes are activated when the modules of the brake having permanent magnets of alternating polarity face one another, wherein each permanent magnet in each array faces and opposes a magnet of opposite polarity. The brakes can be deactivated by displacing one of the modules forward or backward 180 electrical degrees, which causes the magnetic field to diminish to a negligible level.

At present, such brakes are configured to be either fully in phase or out of phase, i.e., shifting the brakes 180 electrical degrees by fully displacing the module forward or backward or by lowering or raising a module away from the braking zone. It is also known to have such brakes configured to shift from one phase angle to another phase angle, e.g., from 180 electrical degrees to 90 electrical degrees, in order to provide an intermediate level of braking force. But no known system provides for the precise shifting of the modules to selected phase angles to provide the application of a number of selected braking forces.

Thus, there exists a need for an apparatus and method that provides for the incremental and precise application of braking force of an eddy current brake. For example, a brake configured to be shifted to any selected phase angle, rather than simply from one phase angle to another phase angle, would be most desirable. And there exists a need to do so with accurate metering, the type of which could not be achieved by a system that employed only double-acting piston cylinders.

It would be further desirable to link such a brake to a control system whereby a selected phase angle, which in turn translates to a selected braking force, could be selected on the basis of a selected condition such as velocity of the incoming vehicle and environmental factors. A system that determines the incoming velocity, for example, an object and applies a precise braking force based on that reading would be desirable. Such a system would allow for precise braking to occur in the event that the object or vehicle approaching the braking zone is not traveling at the designed or intended velocity due to external or unforeseen influences such as temperature, fluctuations in mass, or variable drag coefficients that are imposed on the moving vehicle. In most instances, achieving the desired incremental application of brake force is not possible due to the high difficulty of displacing the opposing modules forward and slightly downward brought on by mechanical interference that occurs surrounding the motor module, and due to the magnetic force between the modules which tends to push the opposing magnets in the module toward equilibrium.



## SUMMARY AND OBJECT OF THE INVENTION

The invention is an incrementally actuated eddy current braking system. The system comprises first and second primary members, which further comprise arrays of permanent magnets arranged in alternating polarity. The respective magnets of the arrays face one another. A means for incremental displacement is drivingly connected to at least one of the primary members.

Thus, it is an object of the invention to provide an electrodynamic brake that can apply a selected brake force incrementally.

It is a further object of the invention to provide an electrodynamic brake that does not have simply two phases, but which can apply a plurality of selected braking forces.

It is still a further object of the invention to provide a system and method that provides a selected braking force based on a condition, for example, velocity or mass of an incoming vehicle, or temperature.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an isometric view of an embodiment of the present invention.

FIG. **2** is a side elevational view of an embodiment of the present invention.

FIG. **3** is a view of an embodiment of the present invention viewing the system along line AB in FIG. **2**.

FIG. **4** is a top view of an embodiment of the present invention.

FIGS. **5**A-**5**D show the displacement of a module having an array of magnets relative to the other module.

FIGS. **6** and **7** are graphs of finite-element-analysis models of the present invention.

FIG. **8** is a schematic of the control system for an embodiment of the invention.

FIG. **9** is a flow diagram showing an embodiment of the invention.

FIG. **10** is a schematic of an embodiment of the invention.

## DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENT OF THE INVENTION

The inventive system **100** is intended to operate in conjunction with a conventional type synchronous linear electrical machine operating as a motor or an electrodynamic brake. An example of such a synchronous linear electrical machine operating as a motor or an electrodynamic brake preferably comprises primary members **300**, **500** comprising arrays of at least two permanent magnets **310**-**380**, **510**-**580** of alternating polarity. The magnets are preferably attached to back plates **200**, **400** which are preferably mounted on primary mounting plate **11**. The magnets along with backplate and plates **10** comprise respective modules **1000**, **2000**. Preferably, a synchronous linear secondary stator member (not shown) accompanies the primary members to provide the synchronous linear electrical machine operating as a motor or an electrodynamic brake. A stator member can be mounted on the bottom of any incoming vehicle a fin-like protrusion that passes through the air gap **40** (shown in FIG. **3**) between primary members **300**, **500** of modules **1000**, **2000**. When the stator member and modules **1000**, **2000** (and in turn the primary members **300**, **500**) move relative to one another, magneto-motive, i.e., braking force, force is created. Such is the operation of an eddy current brake. This invention, however, is concentrated on the primary members **300**, **500** movement relative to one another and therefore discussion of a secondary stator member will be minimal.

The two primary members **300**, **500** oppose each other. It is known to those skilled in the art that if the magnets in opposing primary member arrays **300**, **500** are moved 180 electrical degrees relative to one another (as shown in FIG. **5**D), the electrodynamic brake is fully out of phase and thereby inactive. But if the magnets in the primary member arrays **300**, **500** are incrementally moved relative to one another (as shown in FIGS. **5**A-**5**C), the magneto-motive force created will correspond to the phase angle created by said relative movement. The present invention allows for the incremental movement of a primary member relative to an opposing primary member and in this way provides for a variable electrodynamic braking force.

As shown in FIGS. **1**, **4** and **5**A-**5**D, in a preferred embodiment, the invention comprises two opposing primary members **300**, **500** each comprising arrays of permanent magnets **310**-**380**, **510**-**580**. The first primary member **300** is preferably mounted in a stationary fashion. The second primary member **500** is mounted to a movable plate **10**. The movable plate **10** is preferably an angle weldment. The arrays are preferably mounted to a back plate **200**, **400** which is ferromagnetic. In the completely actuated position, the magnetic array of the primary member **300** in the first stationarily mounted member directly opposes the magnetic array of the second primary member **500** with magnets of opposite polarity facing each other, for example magnets **310**, **320**, **330**, **340**, **350**, **360**, **370**, and **380** directly face and oppose magnets **510**, **520**, **530**, **540**, **550**, **560**, **570**, and **580** respectively. The alignment of the magnets in the arrays of the primary members **300**, **500** when the brake is in the completely actuated position is best shown in FIGS. **1** and **4**, which show the positive magnet of the stationary array **310** directly opposing negative magnet **510** of the movable array. As best shown in FIG. **2**, a carriage **12** is affixed to the movable plate **10** and is slidably engaged with a linear bearing slide **14**. A bracket **16** connects the movable plate **10** to a push rod **22**, said push rod **22** being driven by a means for incremental displacement **20**. The means for incremental displacement **20** is preferably an optically encoded servo-motor operable to linearly displace the push rod **22** in direction A or B. The means for incremental displacement **20** is able to displace the push rod **22** (and therefore the movable plate **10**) to and from a plurality points along pathway AB. The end points of the pathway are only limited by the length of the push rod **22**, the length of the linear slide bearing **14**, or the placement of the cushion bump stops **30**, **32**. The incremental displacement in the invention differs from conventional systems, which only allow for displacement to and from only a few fixed points, most often two fixed points. Incremental displacement according to the present invention allows for modules and primary members to be moved to and from anywhere along a displacement path. Preferably, pressurized cushion bump stops **30** and **32** are affixed to the linear bearing slide **14** so as to limit the motion of the system upon contacting the bump stop supports **36**.

In operation, the means for incremental displacement **20**, by virtue of being drivingly attached to the movable plate **10**, and thus the modules **1000**, **2000**, displaces the second primary member **500** a selected or a predetermined distance along direction AB. Braking force can be varied by the amount of displacement of the second primary member **500** relative to the first **300**. The predetermined displacement distance is determined based on the amount of braking force that is desired to be applied to the moving object having the secondary stator member attached. The module **1000** can be moved relative to the stationary module **2000** a plurality of distances based on the desired braking force. To deactivate the brake completely, the secondary movable module **1000** will be moved completely out of phase as discussed above and as shown in FIG. **5**D. It should be noted while that it is preferred to have one movable module and one stationary module, the invention also encompasses systems wherein both modules **1000**, **2000**, for example, are movable with respect to one another.

An example of the correlation between incremental displacement of the primary members and braking power is illustrated at FIGS. **6** and **7**. FIG. **6** shows five finite-element-analysis models. FIG. **6** shows velocity versus time. FIG. **7** shows force versus time. In FIG. **6**, series **1** shows as a function of velocity over time, a fully engaged operating set of finned modules without any actuation. Series **1** corresponds to the position of the modules shown in FIG. **1**. It can be seen that rate of velocity reduction is greatest when the brake is fully engaged. Series **2** shows the brake's effectiveness in reducing velocity when the primary member is moved 45 electrical degrees out of phase according to the present invention. Series **2** corresponds to the position of the modules shown in Figure SA. It can be seen in Series **2** that rate of velocity reduction is lowered. Series **3** and **4** similarly show a decrease in the rate of reduction and corresponds to the position of the modules shown in FIGS. **5**B and **5**C respectively and caused by moving the member **90** and 135 electrical degrees out of phase. Finally, Series **5** shows a brake that is 180 degrees out of phase, which in this example was 5 linear inches of displacement of a primary member. Series **5** corresponds to the position of the modules shown in Figure SD. It can be seen that at this position, there is no reduction of velocity. FIG. **7** shows corresponding levels of braking force generated by the system.

As schematically depicted in FIG. **8**, another embodiment comprises, the means for incremental displacement **20** in communication with a detection device, which detects a condition, for example, the velocity of the incoming vehicle, temperature, humidity or mass of the incoming vehicle. In an example, the velocity detection device can be of the conventional kind, for example, a set of proximity switches or photosensors of the conventional type in a conventional arrangement that can determine velocity.

As shown in FIGS. **9** and **10**, in the embodiment comprising a velocity detection device **52**, the velocity detection device **52** reads the velocity V of an incoming vehicle **60** and communicates that velocity to a data processor **54**. The data processor **54** comprises an encoded set of instructions **56** and processes the data to calculate the required displacement value DV of the movable module to achieve a desired braking force. The instructions **54** can be in the form of software or can be encoded on an embedded chip in the processor. The data processor **54** processes the data related to velocity instructs the means for incremental displacement **20** and in turn the push rod **22**, to move the desired distance X. In this way, the system provides a system and method that provides a braking level responsive to changes in velocity due to changes in mass, temperature, humidity, and other variables.

While the foregoing has been set forth in considerable detail, it is to be understood that the drawings and detailed embodiments are presented for elucidation and not limitation. Design variations, especially in matters of shape, size and arrangements of parts may be made but are within the principles of the invention. Those skilled in the art will realize that such changes or modifications of the invention or combinations of elements, variations, equivalents or improvements therein are still within the scope of the invention as defined in the appended claims.

What is claimed:

**1**. An apparatus comprising:

a first module comprising a plurality of first permanent magnets arranged linearly along a first module longitudinal axis, wherein all adjacent first permanent magnets along the first module longitudinal axis have substantially opposite polarities;

a second module having a second module longitudinal axis substantially parallel to the first module longitudinal axis, wherein the second module is separated from the first module by a gap sufficient to allow passage of a magnetically reactive member therethrough, and wherein the second module comprises a plurality of second permanent magnets arranged linearly along the second module longitudinal axis, wherein adjacent second permanent magnets have substantially opposite polarities;

a drive for incrementally displacing the second module relative to the first module substantially along the second module longitudinal axis for providing a selective braking force on the magnetically reactive member having a minimum when the first module and the second module are moved substantially out of opposite polarity juxtaposition.

**2**. The apparatus of claim **1**, wherein the drive is an optically encoded servo-motor.

**3**. The apparatus of claim **1**, further comprising a push rod moveable in a direction substantially parallel to the first module longitudinal axis or the second module longitudinal axis.

**4**. The apparatus of claim **3**, wherein end points of a pathway of the push rod are determined by the length of the push rod.

**5**. The apparatus of claim **3**, wherein end points of a pathway of the push rod are determined by one or more cushion bump stops.

**6**. The apparatus of claim **1**, wherein the incrementally displacing allows the second module to move to and from anywhere along a displacement path substantially parallel to the second module longitudinal axis.

**7**. The apparatus of claim **1**, wherein the first module is stationary.

**8**. The apparatus of claim **1**, wherein the minimum selective braking force is substantially zero.

**9**. The apparatus of claim **1**, wherein a maximum selective braking force is provided when the first module and the second module are moved substantially into opposite polarity juxtaposition.

**10**. The apparatus of claim **9**, wherein at the maximum selective braking force all of the first permanent magnets are substantially in opposite polarity juxtaposition with the second permanent magnets.

**11**. The apparatus of claim **1**, further comprising a detector for detecting a condition selected from the group consisting of: velocity of an incoming vehicle, temperature, humidity, mass of the incoming vehicle, and combinations thereof.

**12**. The apparatus of claim **11**, wherein the detector comprises a velocity detector for detecting velocity of an incoming vehicle.

**13**. An apparatus comprising:

a first module comprising a plurality of first permanent magnets arranged linearly along a first module longitudinal axis, wherein adjacent first permanent magnets along the first module longitudinal axis have substantially opposite polarities, and wherein there are no magnets along the first module longitudinal axis between the adjacent first permanent magnets having substantially opposite polarity;

a second module having a second module longitudinal axis substantially parallel to the first module longitudinal axis, wherein the second module is separated from the first module by a gap sufficient to allow passage of a magnetically reactive member therethrough, and wherein the second module comprises a plurality of second permanent magnets arranged linearly along the second module longitudinal axis, wherein adjacent second permanent magnets have substantially opposite polarities;

a drive for incrementally displacing the second module relative to the first module substantially along the second module longitudinal axis for providing a selective braking force on the magnetically reactive member having a minimum when the first module and the second module are moved substantially out of opposite polarity juxtaposition.

**14**. The apparatus of claim **13**, wherein the drive is an optically encoded servo-motor.

**15**. The apparatus of claim **13**, further comprising a push rod moveable in a direction substantially parallel to the first module longitudinal axis or the second module longitudinal axis, and, wherein end points of a pathway of the push rod are determined by the length of the push rod, and, wherein end points of a pathway of the push rod are determined by one or more cushion bump stops.

**16**. The apparatus of claim **13**, wherein the incrementally displacing allows the second module to move to and from anywhere along a displacement path substantially parallel to the second module longitudinal axis.

**17**. The apparatus of claim **13**, wherein the first module is stationary.

**18**. The apparatus of claim **13**, wherein the minimum selective braking force is substantially zero.

**19**. The apparatus of claim **13**, wherein a maximum selective braking force is provided when the first module and the second module are moved substantially into opposite polarity juxtaposition.

**20**. The apparatus of claim **19**, wherein at the maximum selective braking force all of the first permanent magnets are substantially in opposite polarity juxtaposition with the second permanent magnets.

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